Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

J. H. L. VOGT
TRONDHJEM, NORWAY

INTRODUCTION

In a later paper of this treatise (I–IV) are given the physico-chemical laws which govern the *crystallization* of igneous rocks. Subsequently, it will be shown that the same laws can be applied to the explanation of the *chemical composition* of igneous rocks, and consequently also of *magmatic differentiation.*

As I shall often refer to my earlier publications on the problems here discussed, I give a list of those of most importance:

"Studier over slagger," *Svenska Vet.-Akad. Handl.*, 1884. (Stockholm, 1885.)

"Beiträge zur Kenntnis der Gesetze der Mineralbildung in Schmelzmassen und Ergussgesteinen," *Archiv for Mathem. og Naturv.*, Vols. 13 and 14. (Kristiania, 1888–90.)

"Die Silikatschmelzlösungen," I and II. *Kristiania Videnskabs-Selskap*, 1903, 1904.

"Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen," *Tschermaks min. und petrogr. Mitt.*, Vols. XXIV (1905), XXV (1906), and XXVII (1908).

"Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Kristiania Vid.-Selsk.*, 1908.

"On Labradorite-Norite with Porphyritic Labradorite-Crystals: a Contribution to the Study of the "Gabbroidal Eutectic," *Quart. Jour. Geol. Soc.*, 1909.

"Über das Spinell: Magnetit-Eutektikum," *Kristiania Vid.-Selsk.*, 1910.

"Die Sulfid: Silikatschmelzlösungen" (a review, 97 pages), *Norsk Geologisk Tidsskrift* (Kristiania), IV (1917).

"Die Sulfid: Silikatschmelzlösungen. Part I. Die Sulfidschmelzen und die Sulfid: Silikatschmelzen." *Kristiania Vid.-Selsk.*, 1919. Later will appear Part II. Die Nickel-Magnetkies-Lagerstätten.

For geological surveying, chemical analysis, photographs, etc., for this publication I have had contribution from Den Tekniske Hoiskoles Fond (The Foundation of the Technical University of Norway).

ERRATUM

In the article by J. H. L. Vogt, p. 318, in the first line, delete the words "a later paper of."

I

REVIEW OF THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION OF IGNEOUS MAGMAS

In the examination of these laws two different methods can be used: (*a*) the *synthetic*, in which there is an opportunity for precision-determinations, especially of temperature. Previous investigations on the crystallization of silicates from melts have been, nearly without exception, conducted at the pressure of one atmosphere; (*b*) the *analytic*, mainly based on the study of the structure of the rocks. In this manner we may examine the sequence of crystallization, and so also the "individualization-fields" of the minerals, further the mix-crystal systems, the chemical composition of eutectic intergrowths, etc.—all under the physical conditions, especially with regard to pressure and time, present during the solidification of the different igneous rocks.

The synthetic method forms the important base. The analytic method gives us, in particular, information as to the extent to which the results of investigations conducted chiefly at atmospheric pressure and during short periods of time, can be transferred to apply to the physical conditions under which the crystallization of magmas took place.

The two methods, therefore, go hand in hand and complete each other.

REMARKS ON THE STRUCTURAL CRITERIA FOR THE SEQUENCE OF CRYSTALLIZATION

The sequence of crystallization in igneous rocks may usually be determined by the complete, partial, or wanting idiomorphism of the minerals, by the inclusions, by deposition on a solid body (*Fixkörper-Absatz*), by "together-swimming" structure (*synneusis-struktur*, see below), by law-governed intergrowths, etc.

The complete *idiomorphism* of a primary mineral A against all the other minerals shows that its crystallization was finished before the commencement of the solidification of the others. From the partial idiomorphism of the primary mineral A against the primary mineral B whose idiomorphism is wanting, we can infer that the crystallization of A had commenced at an earlier stage than the crystallization of B. But we must not draw the more extensive conclusion that A in its entirety had crystallized before the commencement of the crystallization of B. As to the conceptions allotriomorphism, hypidiomorphism, and panidiomorphism, we refer to the petrographic textbooks.

Inclusions of an idiomorphic, primary crystal A in B implies that A had crystallized earlier than the surrounding parts of B. But if A only appears in the exterior zone of B, the interior part of B may have crystallized earlier than A. And even if inclusions of idiomorphic crystals of A appear evenly distributed over the whole of B, also in the kernel of B, it may be that part of A also may have crystallized at a later stage. As an example, idiomorphic crystals of apatite, as is known, in many cases appear in the oldest silicates and in the ore minerals, indicating that the apatite crystallized before the commencement of the solidification of the iron ore and the silicates. But I warn against the conclusion, which is often drawn, that the apatite in its entirety crystallized during the earlier stage.

Further, it must be taken into consideration that small portions of the mother-liquid occasionally may be inclosed or included in a mineral during its growth. As example we refer to the well-known zonally arranged glass-inclusions in leucite, sanidine, etc., in many dyke and effusive rocks. If corresponding magma-inclusions occur in deep-seated rocks, a complete crystallization of this material will take place. Thus the result will be inclusions in the host of a later-crystallized mineral.

Inclusions of mineral A in mineral B may furthermore be due to the fact that A originally, at high temperature, occurred as a solid solution in B, and that afterward, owing to reduced solubility by decreasing temperature, A separated from the solid solution. As an example we refer to the well-known inclusions of perthitic albite or albite-oligoclase in the microcline of granites, etc. The microcline (or orthoclase) dissolved about 28 per cent Ab+An, the greater part of which later separated during refrigeration. Further may be mentioned the secretion of lamellae of monoclinic pyroxene in orthorhombic pyroxene[1] and conversely also of orthorhombic pyroxene in monoclinic.[1] In the same manner the well-known microscopic inclusions, often with idiomorphic contour, of titanic iron ore in hypersthene, diallage, and plagioclase of gabbros may be explained.[2] The latter inclusions were often interpreted by earlier investigators as older than the host-mineral, but in their present form they must be explained as later secretions from an originally solid solution. As may be understood from this account concerning the inclusions we must take into critical consideration a great number of momentums in determining the successive age of the minerals.

---

[1] Cf. the general account in my publication in *Tscherm. min. u. petrogr. Mitt.*, Vol. XXIV (1905), pp. 537–42.

When a substance is segregated from a solution, it often, as is well known, adheres to a solid already present (solid body or *Fixkörper*). The result of this is the *deposition on a solid body* (*Fixkörper-Absatz*), which is also very important in the solidification of igneous rocks. We may here, for instance, refer to Figure 34, illustrating the deposition of spinel on pyrite; to Figure 33, illustrating the deposition of titanomagnetite on olivine; and to Figure 35, where in one place pyrite has been deposited on apatite while in another apatite has been deposited on pyrite.

The individuals of a mineral, segregated from a magma at an early stage, frequently swam together to assemblings or aggregates, the result of which is a structure, for which I propose the term *together-swimming structure* or *synneusis structure*.[3]

This together-swimming may occur very rapidly. I refer to my publication "Die Sulfid: Silikatschmelzlösungen" (I, 1919), Figure 11, illustrating assemblages of octahedrons of magnetite in a bessemer-matte, consisting chiefly of Cu_2S, and to Figure 28, *a*, illustrating assemblages of small individuals of zincblende in a slag. The solidification period of the two molten masses just mentioned, respectively molten sulfide and molten slag, needed only a very short time, at most half an hour.

---

[1] W. Wahl, "Die Enstatitaugite," *Tscherm. min. u. petrogr. Mitt.*, Vol. XXVI (1906).

[2] In this connection we refer to a treatise by A. Johnsen, "Regelmässige Einlagerung von Eisenglanz in Cancrinit," *Centralbl. f. Min., Geol. und Pal.*, 1911, and by O. Andersen, "On Aventurine Feldspar," *Amer. Jour. Sci.*, Vol. XL (1915).

[3] Composed of *σύν*, *syn*=together and *νεῦσις*, *neusis*=swimming.

The phenomenon here discussed may, as to igneous rocks, be illustrated by Figure 1, representing a dunite from the Hestmandö-field in the northern part of Norway, with an average of only about 1 per cent chromite. In some parts of the thin section chromite is entirely or almost entirely lacking, but in other places we may find aggregates of ten to twenty small octahedrons of chromite which, as well with reference to the idiomorphism against the olivine as with reference to the together-swimming structure, must have crystallized while the olivine was still in a molten condition. From this and other dunite rocks with a little chromite we may draw the conclusion that the chromite commenced crystallizing earlier than the olivine, when there was at least 1 or 0.5 per cent, perhaps only 0.33 per cent, chromite present. But

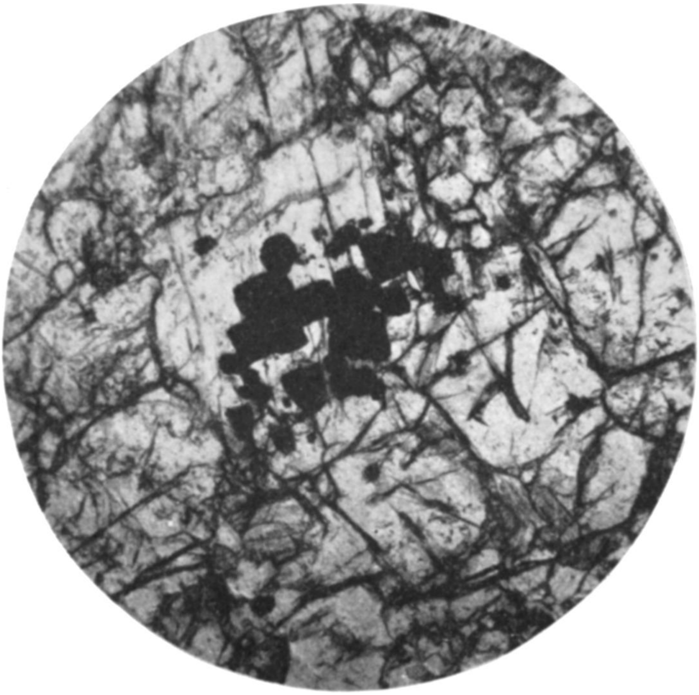

FIG. 1.—Dunite from the Hestmandö-field, northern Norway. Groups of octahedrons of chromite, illustrating "together-swimming" or synneusis structure. (Photo. 25:1.) (Black = chromite, white = olivine.)

this does not exclude that the olivine may have commenced crystallizing earlier than the chromite when the latter only amounted, for example, to 0.1 or 0.05 per cent. The earlier silicate minerals, for example, olivine in olivine-rich gabbros, and hypersthene or diallage in hypersthene- or diallage-rich gabbros, also often show the together-swimming structure, as in Figures 10, 12, 13, 20 and 21, and 33.

The *relative commencement* of the solidification, especially of the minerals that commence crystallizing at a somewhat early stage, may often quite easily be decided by the structure. On the other hand, the allotriomorphism of a mineral C, against the minerals A and B, shows that C only commenced crystallizing after an often quite essential part of A and B had already solidified. Especially where the later mineral C is present in a small quantity, its allotriomorphism in connection with its appearance as *Zwischenklemmungsmasse* (or mesostasis) presents an easily recognizable criterion that it belongs to a very late stage of the crystallization. But at this late stage the minerals A and B will in many cases have continued forming. We refer to the explanation given in connection with Figures 17 and 18.

The *simultaneous crystallization* of two or more minerals may be manifested in various ways. With two simultaneously crystallizing minerals, each may grow until the individuals of A happen to collide with the individuals of B. Or some of the segregating mineral A may be deposed on the already solidified crystals of B, and some of the simultaneously segregating mineral B on the already solidified crystals of A.

In this manner we may observe crystals of plagioclase with quite good idiomorphic contour against the hypersthene or diallage and, further, crystals of hypersthene or diallage with quite good idiomorphic contour against plagioclase in the same thin section of an anchi-eutectic norite or gabbro. In the deep-seated rocks it may in such cases often be quite impossible to decide which of the two minerals first commenced crystallizing.

It may also often occur that the two minerals crystallize in an intimate intergrowth. In this manner simultaneously crystallizing feldspar and quartz, as is well known, sometimes produces micropegmatitic or granophyric structure, as in graphic granite. Corresponding structure, which gives an evidence of a crystallization along a eutectic boundary curve, or exceptionally by a binary (or ternary or still more complex) eutectic, is also sometimes found with other minerals, for instance, between olivine and magnetite (see Fig. 28).

In many, possibly in most, cases the crystallization of the minerals A, B, C, etc., takes place in the following manner: Each mineral begins crystallizing at its proper stage, and continues to grow until the entire magma has solidified. As an extreme example we may choose apatite. This phosphate is only slightly soluble in silicate magmas at temperatures just above that at which the silicates commence to crystallize. If there is 0.20 per cent apatite present, the essential portion, perhaps 0.18, 0.19, or 0.195 per cent, has already crystallized before the silicate minerals have commenced segregating. But we may be pretty certain that a trifle phosphate, 0.02, 0.01, or perhaps only 0.005 per cent, still exists in solution at this stage and little by little solidifies later. It has, however, not been possible for me to substantiate this by observation with respect to the apatite; but I have been able to establish that spinel, when present only as 0.01 or at most 0.02 per cent, only commenced crystallizing after a great part of the silicate mineral A had solidified. (See Fig. 33 and the chapter on spinel.)

Fe_3O_4 and the different ferromagnesian silicates are only slightly soluble in acid—or granitic—magmas, and therefore commenced crystallizing at an early stage. We find, however, as is discussed below, a small remnant of magnetite and ferromagnesian silicate in the final product of the solidification. We may consequently draw the conclusion that the essential part of the magnetite and the ferromagnesian silicate was certainly solidified during the first stage of the crystallization, but that a little remnant stayed in the solution and was solidified later.

In a binary system, type IV, of two discontinuous mix-crystals—A, melting at relatively high temperature (for example, FeS_2, at high pressure), and B, melting at relatively low temperature (for example, FeS)—idiomorphic crystals of B never appear in A, but, on the contrary, idiomorphic and usually somewhat resorbed crystals of A appear in B. Here the sequence of crystallization, without regard to the proportion of weight between A and B, is first A and later B, and this to be understood thus, that the crystallization of A was *completed* before that of B began. (See Fig. 36.)

In the usual silicate eruptives, most frequently consisting of a whole series of components, we may also meet corresponding crystallization of a certain mineral, completely solidified at a relatively early stage. See Figures 20 and 21, representing crystals of hypersthene imbedded in diallage.

Another case of crystallization *completed* at an early stage is illustrated by Figures 8 and 9 (and a theoretical explanation given below) with crystallization at the beginning stage of hypersthene, while the Fe-Mg silicate at a later stage entered into biotite.

In this treatise (Part I) we are only going to consider the solidification of the rocks (the transition from liquid to solid phase). We, however, also discuss the continued change of the minerals, which may be founded on the later crystallization of a substance originally in solid solution, and furthermore we are going to deal with the reactions which appear in the solid phase on the boundary between two minerals, and which are an immediate result of the cooling of the rocks after completed crystallization. We shall, however, not discuss the later changes, which are not a direct result of the solidification of the rocks, but are founded on exterior incidents, as, for instance, dynamo and contact metamorphosis, chemical actions, etc.

INTRODUCTORY REMARKS CONCERNING THE APPLICATION OF THE PHYSICO-CHEMICAL LAWS TO THE CRYSTALLIZATION OF MAGMAS

Magmas usually consist of a whole series of components, which entail a complication of the equilibrium existing in the magma and consequently also of the laws of the crystallization.

In many cases, however, an essential simplification of these complications takes place, as, according to H. E. Boeke,[1] the following assertion is applicable: "The saturation-boundary between binary mix-crystals as well as in general the equilibrium between two solid phases of a binary system do not change by contact with other phases and components, when these new entering components do not form solid solutions or stoechiometric compounds with the former solid phases." The proportion between An and Ab in the segregated plagioclase mix-crystal will in this manner be the same whether the crystallization takes place in a pure An+Ab melt or in a silicate melt (or magma) which besides plagioclase also delivers, for instance, magnetite, olivine, etc.

---

[1] *Grundlagen der physikalisch-chemischen Petrographie* (1915), p. 104.

In order to investigate the laws of crystallization of the principal components of the magma, we may generally leave the components which are present only in subordinate quantity out of consideration, provided that the latter do not form solid solutions or enter into mix-crystal combinations with the principal components. We must, however, take into consideration that when A, B, and C form a ternary eutectic, and C only is present in small quantity, the simultaneous crystallization between A and B, along the eutectic boundary between A and B, will not be identical quantitatively with the composition of the binary eutectic between A and B. If C, however, is present in minimal quantity, the difference between the point in question on the eutectic boundary between A and B and the binary eutectic A:B will be so inconsiderable that it practically may be left out of consideration.

THE FELDSPARS, AB:AN, OR:AB+AN.

The binary system *Ab*:*An* (with melting-point Ab = 1100 ± 10° and An = 1550° ± 2°) belonging to mix-crystal type I has been studied in detail by N. L. Bowen[1] of the Geophysical Laboratory of the Carnegie Institution of Washington at the pressure of one atmosphere (and with chemically pure substances). We reprint Bowen's graphic exhibit as Figure 2, where the great horizontal difference between the liquidus and solidus curves is shown.

As an example we may mention that from a molten mass, Ab_1An_1, the first mix-crystal, separating at 1450° (without supersaturation), has a composition nearly exactly $Ab_{20}An_{80}$, or Ab_1An_4. Even before Bowen's investigation (1913), I had (see especially *Tscherm. Mitt.*, Vol. XXIV [1905]), on the basis of the well-known zonal structure of the plagioclases, and further on the basis of the proportion between Ab:An in the total plagioclase calculated from the analysis of the rocks and in the first segregated crystal, decided that the system Ab:An belongs to type I, and, furthermore, that in the crystallization of plagioclase in eruptive rocks, especially in dike and effusive rocks, there is a very great horizontal difference between the liquidus and the solidus curves.

---

[1] *Amer. Jour. Sc.*, Vol. XXXV (1913).

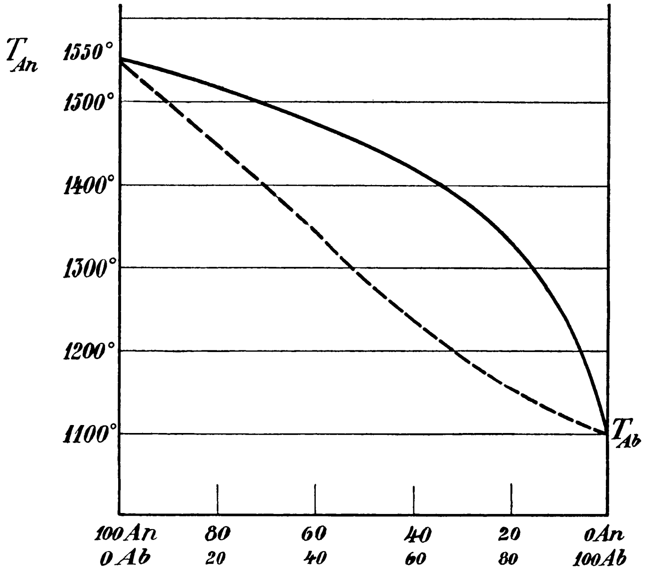

FIG. 2.—The melting-diagram, An:Ab, after Bowen

The binary diagram for Ab:An, at the pressure of one atmosphere and for 100 per cent Ab+An, may with unessential modifications of the horizontal difference between the two curves (see a following chapter) be transferred to magmas, crystallizing at high pressure, which besides Ab and An contain other components. The investigation of the mix-crystal system and the proportion between the liquidus and solidus curves for Ab:An may consequently also be applied to rocks, which besides plagioclase also contain a great quantity, 40 per cent and still more, of foreign components, as quartz and Fe-Mg silicates. Petrographic experience proves that in such rocks we can detect no difference in the horizontal distance of the two curves, and this is in best accordance with the general law cited on page 326.

Or:Ab or Or:Ab+An.—Because of the extreme viscosity which characterizes melted $KAlSi_3O_8$ and $NaAlSi_3O_8$ (without or with only a small quantity of $CaAl_2Si_2O_8$), the synthetic study of the system Or:Ab or Ab+An is connected with exceptionally great difficulties. We may therefore here use the analytic method, cf. my earlier publication in *Tscherm. Mitt.*, Vol. XXIV (1905).

When Or is predominant, orthoclase first crystallizes, and when Ab+An is predominant, plagioclase first. The boundary ("individualization-boundary") is decided by the following method of investigation:

In a number of rocks, where the proportion Or:Ab:An in the entire rock was determined on the basis of the rock analysis, we find crystallized as No. I: *plagioclase* at 32, 32, 32.5, 32.5, 33.5, 34, 36, 36, 37.5, 39.5, 40, and 41 Or:Rest Ab_{+An}; *orthoclase* (or microcline) at 42, 43, 43.5, 43.5, 46, 47, 47, 50, 50, 50.5, 52, and 52.5 Or:Rest Ab_{+An}.[1] Ab_{+An} here represents Ab with a small but variable quantity of An, consequently albite, oligoclase, and andesine.

Between the two "individualization-fields" lies the boundary for orthoclase: albite, oligoclase, or andesine at about 0.4 Or:0.6 Ab or Ab_{+An}, perhaps nearest 0.42 Or:0.58 Ab_{+An}, applying to magmas at high pressure and with predominant Or+Ab+An with some mixture of other components. This boundary must be interpreted as an eutectic boundary curve.

When orthoclase (or microcline) crystallizes at *high* temperatures from granitic magmas, which besides predominant Or also contain a good deal of Ab_{+An}, there enters in the orthoclase up to about 30 per cent (or 28 per cent) of Ab_{+An}, which is partially separated by the cooling of the solid solution as albite or albite-oligoclaseperthite. By the crystallization of acid plagioclase, the latter absorbs up to about 10 per cent (or 12 per cent) Or, which on cooling may give anthiperthite. Basic plagioclase (labradorite-bytownite) seems to absorb a somewhat smaller quantity of Or. Concerning this matter we refer to the chapter on the anorthosites in Part II.

---

[1] Two uncertain determinations with 38 and 36 Or are here left out of consideration.

By the above-mentioned crystallization in the acid magmas of Or and Ab (or Ab_{+An}) there result two minerals: orthoclase about 0.7 Or + 0.3 Ab (or Ab_{+An}), and acid plagioclase, about 0.9 Ab (or Ab_{+An}) + 0.1 Or.

Orthoclase and albite have almost exactly the same melting-point, and almost exactly the same atomic weight, probably also about the same latent melting-heat, etc. Granted a binary eutectic system (type V), the eutectic must lie almost exactly midway between 0.7 Or + 0.3 Ab and 0.9 Ab + 0.1 Or, consequently at 0.4 Or:0.6 Ab, just as we found above.

As An has a far higher melting-point than Or (and also than Ab), it is likely that the eutectic boundary between orthoclase and plagioclase with decreasing Or is characterized by increasing An in the plagioclase. In this manner we shall probably find the individualization-boundary between orthoclase and labradorite at 0.45—0.5 Or:0.55—0.5 Ab_{+An}.

This explanation is, however, not explicit, as we have not taken into consideration that in certain rocks or under certain conditions, the details of which we are not acquainted with, the two independent minerals, orthoclase and albite (or some other acid plagioclase), do not appear, but instead we find the mineral anorthoclase.

In my treatise in *Tscherm. Mitt.*, Vol. XXIV (1905) I pointed out the fact that a whole series of analyses of anorthoclase shows relations about 0.4 Or:0.6 Ab (or about 0.42 Or:0.58 Ab_{+An}) and I set forth the hypothesis that the anorthoclase might be defined as a microscopical or submicroscopical eutectic intergrowth of orthoclase (microcline) and albite (or some other acid plagioclase). This hypothesis is, however, quite dubious, and the physicochemical interpretation of the anorthoclase is still an open question.

QUARTZ (QU) AND FELDSPARS. QU:OR, QU:AB, QU:AN, QU:AB+AN, QU:OR:AB+AN

The binary system $SiO_2:CaAl_2Si_2O_8$ (*An*) has been examined by G. A. Rankin and Olaf Andersen[1] (at the Geophysical Laboratory, Washington) with the result: An, melting-point = 1550° ± 2°; Eutectic SiO_2:An = 52 per cent An:48 per cent SiO_2, melting-point 1353° ± 2°.

According to I. B. Ferguson and H. E. Merwin[2] (1918) the melting-point for tridymite is 1670 ± 10°C; for cristobalite 1710 ± 10°C. K. Endell and R. Rieke[3] (1912) decided for cristobalite 1685 ± 10°. N. L. Bowen[4] decided a somewhat lower temperature, and C. N. Fenner[5] thought he might fix the melting-point of cristobalite at 1625°, which, however, according to the latest precision-investigations, must be a little too low.

It is a matter of course that *Qu and Or*, as well as *Qu and Ab*, in the same manner as Qu and An, must form a binary eutectic. Because of their extreme viscosity the binary eutectics Qu:Or and Qu:Ab are not experimentally determined. We may therefore here use the analytic method.

We shall commence with *graphic granite*, the structure of which, as already established many years ago by W. C. Brögger,[6] is due to a simultaneous crystallization of quartz and feldspar. That is to say, the crystallization took place at a eutectic point or along a eutectic boundary curve.

Referring to my earlier publications[7] on the problem in question, we are going to give a collocation of all the hitherto published usable or at any rate somewhat usable analyses of graphic granite from pegmatitic granite dikes.

---

[1] The System Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, Vol. XXXIX (1915).

[2] *Amer. Jour. Sci.*, Vol. XLVI (1918).

[3] *Zeitschr. f. anorg. Chemie*, Vol. LXXIX (1913).

[4] *Amer. Jour. Sci.*, Vol. XXXVIII (1914).

[5] *Ibid.*, Vol. XXXVI (1913).

[6] *Geol. Fören. Förh.*, Vol. V (1881), and *Zeitschr. f. Kryst. Min.*, Vol. XVI (1890), I, pp. 148–59.

[7] "Silikatschmelzlös.," II (1904), and *Tscherm. Mitt.*, Vol. XXV (1906).

TABLE I

	No.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Total
	Microcline Graphic Granite										
Norway	1	74.04	14.40	Nil	Nil	Nil	0.33	2.01	9.36	Nil	**100.18**
	2	74.00	14.31	Nil	Nil	Nil	0.39	2.42	9.02	Nil	**100.14**
	3	73.82	14.44	Nil	Nil	Nil	0.35	2.45	8.90	Nil	**99.96**
	4	74.47	15.13	Nil	Nil	Nil	....	....	.....	.....	**......**
	5	73.70	14.11	Nil	Nil	Nil	0.39	3.04	8.72	Nil	**99.96**
Sweden	6	72.41	14.51	0.30	....	Nil	0.13	2.19	10.09	0.28	**99.91**
	7	74.58	13.37	0.24	....	Nil	0.32	1.16	9.80	0.57	**100.04**
United States	8	73.89	13.75	0.26	....	Nil	Nil	2.10	9.00	0.24	**99.24**
	9	73.92	14.26	0.30	....	Nil	Nil	2.06	8.90	0.11	**99.64**
	10	72.76	15.44	(InAl_2O_3)	....	Nil	0.19	2.35	9.28	0.15	**100.20**
	11	72.80	15.07	0.26	0.21	Nil	Nil	3.35	7.92	0.30	**99.91**
	Oligoclase Graphic Granite										
Norway	12	76.8	14.2	Nil	Nil	Nil	1.7	6.1	1.5	....	**100.3**
Sweden	13	76.67	14.20	0.14	....	0.04	2.67	5.33	0.52	0.48	**100.04**

EXPLANATION

Nos. 1–5 and 12, see "Silikatschmelzlös.," II. No. 1 from Arendal; Nos. 2–3 from Hitterö; No. 4 from Raade; No. 5 from Arendal is industrially pulverized graphic-granite, in which a trifle surplus feldspar is not excluded. In all these analyses a small loss (0.1–0.3 per cent) caused by ignition is deducted. The precipitate of Al_2O_3 was in all cases entirely white, and on account of this a special analysis of iron was not made. Some iron, less than 0.1 per cent Fe_2O_3, is, however, not excluded. No. 12, approximate analysis from Evje. Nos. 1 and 5 were analyzed by A. Grönningsæter and E. A. Dalset, assistants at the time. Nos. 2–4 and 6 were analyzed by students. K_2O,Na_2O and CaO in No. 4 have not been included on account of less accuracy.

Nos. 6, 7, and 13 from A. Bygdén, *Bull. of the Geol. Inst. of Upsala*, Vol. VII (1906); from Elfkarleö, Skarpö, and Ytterby.

Nos. 8–10 from Edson S. Bastin, *U.S. Geol. Surv. Bull. 420* (1910); from Topsham, Me., and Redford, N.Y. (No. 10, a little Fe_2O_3 [n.d.] in Al_2O_3.) No. 11 from Hiriart Hill, Cal., analyzed by W. T. Schaller, cited by H. S. Washington, "Chemical Analysis of Igneous Rocks, 1884-1913," *U.S. Geol. Surv. Prof. Paper 99* (1907). (Cited below as Wash.)

In the above table I have not included: Analysis of oligoclase graphic granite from the West Indies in Bygdén's treatise (Wash., p. 267, No. 5, with 68.12 per cent SiO_2), as this specimen is greatly decomposed, with considerable new-formed epidote, etc. This analysis can therefore not be used in the determination of the proportion of quartz and feldspar.

Analysis No. 4 in E. S. Bastin's treatise (Wash., p. 108, No. 4, with only 71.00 per cent SiO_2), as Bastin informs us of this specimen: "Some small areas of pure feldspar were associated with the graphic granite in this specimen, so that the silica percentage shown in the analysis is lower than it would be for graphic granite alone." The same is probably also the case of an analysis, by A. W. Howitt, 1888, from Victoria (Wash., p. 112, No. 30).

With respect to the other analyses which are noted in Washington's Index as graphic granite we remark: "The graphic microgranite," page 73, No. 2 (with 3.74 per cent Fe_2O_3, 2.81 per cent FeO), represents a rock, and not graphic granite. The same also applies to No. 19, page 94 (with 0.73 per cent Fe_2O_3, 0.78 per cent FeO, 0.99 per cent MgO).

In the treatise, above cited, by Bygdén, as also in a treatise by H. E. Johansson,[1] an analysis by P. J. Holmquist[2] has been taken as an example of an albite-graphic granite, showing 77.32 per cent SiO_2, 0.34 TiO_2, 11.62 Al_2O_3, 1.57 Fe_2O_3, 0.69 FeO, 0.10 MnO, 0.62 CaO, 0.80 MgO, 0.99 K_2O, 5.81 Na_2O, 0.65 H_2O, *total* 100.51. This was computed by Holmquist as: 39.0 per cent Qu, 49.3 Ab, 4.6 Or, 1.9 An, also 2.4 chlorite, 2.3 magnetite, 0.8 titanite, 0.3 water, and a little calcite. The analysis is from a thin dyke in diabase (Rödö) and does not permit any exact determination of quartz: albite in graphic granite.

The precision-determination of the quantitative proportion of quartz and feldspar is complicated partly because of the inevitable errors in the analyses, of which more below, and partly because we cannot always be certain that the analyses represent absolutely pure intergrowths of the two minerals. In granite-pegmatite dikes we sometimes meet specimens of which one part consists of pure feldspar, free from quartz, and the other part of graphic granite, retaining the crystallographic orientation of the feldspar. That is to say, some feldspar first crystallized alone, and later, having reached an eutectic boundary curve, it continued its growth simultaneously with quartz. Sometimes we may find in the center of a large specimen of graphic granite small parts of pure feldspar. In such cases, the analyses of course cannot be used for precision-determinations of the relative proportions of quartz and feldspar. We may here refer to Bastin's remarks concerning his analysis No. 4.

On the basis of the analysis, we are going to calculate the quantitative proportions of quartz and feldspar in our microcline-graphic granites, according to the following methods:

---

[1] *Geol. Fören. Förh.*, Vol. XXVII (1905).

[2] *Sveriges Geol. Unders.*, C. 181 (1899).

a) Originating from K_2O, Na_2O, and CaO we calculate the quantity $KAlSi_3O_8$ (Or), $NaAlSi_3O_8$ (Ab), and $CaAl_2Si_2O_8$ (An), and when this is done the sum of feldspar is deducted from the analytically determined sum of SiO_2, Al_2O_3, K_2O, Na_2O, and CaO. The difference is quartz. This method contains a very great source of error, as an error in the determination of K_2O, Na_2O, or CaO in the calculation of the amount of feldspar will be doubled respectively 6, 8.5, or 5 times. To this may be added the inaccuracy in the SiO_2 determination.

b) Originating from the proportion $K_2O:Na_2O:CaO$ we calculate the percentage of SiO_2 in the feldspar (ex. 65.28 per cent in No. 1) and then we calculate the proportion between quartz (n) and feldspar ($1-n$), ex. for No. 1.:$n.\ 100+(1-n).\ 65.28=74.04$. A relative error in the determination of K_2O, Na_2O, or CaO will in this manner be eliminated. But an error in the determination of SiO_2 will be doubled nearly three times.

We have a control of the calculation, in method (*a*), in the calculated percentage of Al_2O_3 in the feldspar, compared with the percentage of Al_2O_3 found in the analysis. As an example, No. 5 shows 1.06 per cent too much Al_2O_3 in the calculation, consequently also too much feldspar, and so too little quartz. The calculated 21.58 per cent quartz must consequently be increased. On the other hand, No. 9 shows 1.12 per cent too little Al_2O_3 in the calculation, consequently too little feldspar or too much quartz.

With combined consideration of both methods of calculation, and of the sum of the analysis minus ignition and Fe_2O_3, we have under C written the probable percentage of the quartz. The rest is feldspar.

TABLE II

No.	A					B	C
	Qu	Or	Ab	An	Al_2O_3	Qu	Qu
1........	25.60	55.51	17.05	1.64	−0.34	25.23	**25.4**
2........	24.34	53.50	20.52	1.94	+0.16	24.90	**24.6**
3........	24.54	52.78	20.78	1.74	−0.12	24.25	**24.4**
5........	21.58	51.72	25.78	1.94	+1.06	23.52	**23.5**(+?)
6........	20.55	59.84	18.57	0.65	+0.28	19.28	**20.3**(+?)
7........	29.43	58.12	9.84	1.59	−0.25	27.53	**28.5**(+?)
8........	27.01	53.38	17.82	....	−0.53	23.57	**25.3**
9........	27.32	53.32	17.47	....	−1.12	23.67	**25.5**
10........	22.94	55.04	19.94	0.95	−1.18	20.79	**21.9** (?)
11........	22.79	46.97	28.41	....	−0.97	19.19	**21.0** (?)

The specimen No. 6 is an erratic block (with 0.30 per cent Fe_2O_3 and 0.28 per cent ignition). Here a minimal, hardly perceptible, decomposition is not excluded, so the determination 20.3 per cent quartz (or according to Bygdén 20.81 per cent) is probably too low. For No. 11 I have no supply of the original literature. The analysis shows 0.26 per cent Fe_2O_3, 0.21 FeO, and 0.30 ignition, and to the calculated result is added an interrogation point.

Arthur Holmes[1] has used another method in order to determine the quantitative proportions of quartz and feldspar in graphic granite from dikes of granite-pegmatite (in Mozambique), viz., Rosiwal's planimetric method. In this manner, from different localities, he found quartz amounting to 27.9, 27.1, 26.3, 25.6, 25.3, and 24.2, average 26.1 per cent (calculated in percentage by weight) and rest, 73.9 per cent of microcline with the ordinary perthitic admixture of albite-oblioclase. Consequently we have the following determinations of the quantity of quartz in microcline graphic granite:

Calculated from the quantitative analyses: 28.5 (too high ?), 25.5, 25.4, 25.3, 24.6, 23.5 (?), 21.9 (too low?), 21.0 (?), and 20.3 (too low ?).

By the Rosiwal method: 27.9, 27.1, 26.3, 25.6, 25.3 and 24.2 per cent of quartz.

The majority of these determinations are subject to great sources of error, which may amount to several per cent. If we take this into consideration, I think I am justified in drawing the conclusions that the proportions of quartz and feldspar in microcline graphic granite from dikes of pegmatite are subject only to small variations or are practically constant, and that we may fix the proportion pretty closely at:

26 per cent quartz:74 per cent microcline.[2]

The graphic granite in granite-pegmatite dikes crystallized at a relatively late stage, viz., after the essential part of the mica and, most frequently, also a part of the feldspar had solidified. Only a trifle mica was left at the time for the forming of the graphic granite. But in addition to this, besides the components of the feldspars and the quartz, there was surely some H_2O present, possibly partly connected with SiO_2 in forming a separate component (as H_2SiO_3 [?]). The graphic granite will thus have crystallized from a solution, which consisted predominantly of the components of feldspar and quartz, but also of a little mica and a small quantity of a component, as H_2O and H_2SiO_3 (?). The graphic granite has in this manner crystallized at a eutectic boundary curve, located *quite close* to the eutectic between the microcline components and quartz.

---

[1] *Quart. Jour. Geol. Soc. London*, Vol. LXXIV (1919), p. 77.

[2] In "Silikatschmelzlös.," II (1904), I gave the proportion 25.75:74.25, which is practically the same.

As microcline (from dikes of granite-pegmatite) always contains considerable Ab_{+An}, most often 25–30 Ab_{+An}:75–70 Or, it almost certainly has a somewhat lower melting-point than pure Or, and we must therefore assume that the eutectic Qu:Or contains a little more Qu than the eutectic Qu:microcline.

As the binary eutectic we shall assume 28 Qu:72 Or. As pure Ab has nearly the same melting-point as pure Or, nearly the same molecular weight (Or = 279.4, Ab = 263.3), and possibly also almost exactly the same melting-heat, it must be supposed that the eutectic Qu:Ab holds about the same percentage of Qu as the eutectic Qu:Or. As an approximation we may consequently assume 28 Qu:72 Ab as the binary eutectic.

QU:AN AND QU:AB, QU:OR

For the pressure of one atmosphere we have the synthetic determination: $E_{Qu\text{-}An} = 48\ Qu^1 : 52\ An$, at 1353°. Further we refer to the determinations just mentioned (for a very high pressure):

$$E_{Qu\text{-}Or} = ca.\ 28\ Qu:72\ Or$$
$$E_{Qu\text{-}Ab} = ca.\ 28\ Cu:72\ Ab.$$

Even if an error of a few per cent may be found in the latter statements, it is evident in any case that the binary eutectic Qu:Or or Qu:Ab contains much less quartz than the binary eutectic Qu:An. This is in accordance with Ab (as well as Or) having an essentially lower melting-point, in round numbers 450°, than An.

The course of the melting-curve (see Fig. 3) on the Qu side in the neighborhood of Qu will be about the same, whether the second compound is An or Ab (or Or). If we extend the curve, experimentally determined for $E_{Qu\text{-}An}$ on the quartz side, and draw the curve on the feldspar side for $E_{Qu\text{-}Ab}$ (respectively $E_{Qu\text{-}Or}$) about parallel with $E_{Qu\text{-}An}$, a binary eutectic $E_{Qu\text{-}Ab}$ (respectively $E_{Qu\text{-}Or}$) will appear with composition about 25–30

---

[1] Qu here signifies christobalite from the melting-point to 1470° and tridymite from 1470° to 1353°.

Qu:75–70 Ab (or Or), just as we have in reality derived from the analyses of the graphic granites.

As the melting-points as well as the binary eutectics (as will be shown in a following chapter) are only very little displaced by pressure, we are justified in drawing a parallel between the eutectic SiO_2:An, determined for low pressure, and the eutectic SiO_2:Ab (or SiO_2: Or), calculated for high pressure. The case is somewhat complicated, however, by the fact that SiO_2 in one case is tridymite but in the other quartz.

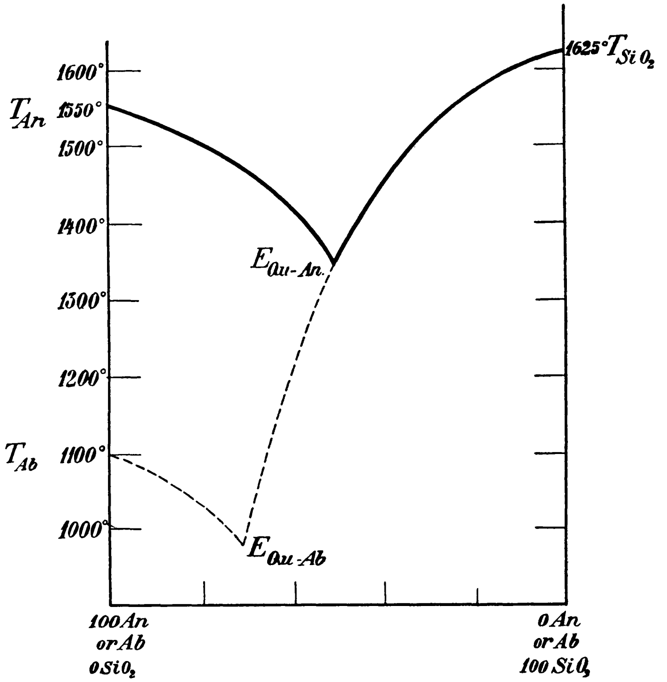

FIG. 3.—Melting-diagram, An:SiO_2 (after Bowen), and Ab:SiO_2 (schematic after Vogt).

The melting-point for the binary eutectic $E_{Qu\text{-}Ab}$ (or $E_{Qu\text{-}Or}$) must, according to the nature of the case, lie considerably lower than the melting-point of pure Ab (or Or), consequently considerably lower than 1100° and certainly somewhat lower than 1000°. As an estimate we set it at 975°, which should be approximately correct.

Qu:Ab+An.—In a *ternary* system consisting of two components (as, for instance, Ab and An), which form a binary mix-crystal system of type I, and a third component independent of the former (as Qu or $CaMgSi_2O_6$), there appear, according to F. A. H. Schreinemaker's theoretical investigations,[1] two melting-surfaces (Fig. 4), which intersect in a curve, viz., "eutectic boundary-line"[2] or briefly a "eutectic line or curve." Three subcases may occur, accordingly as the eutectic boundary-line ($E_{\text{Qu-An}}$ to $E_{\text{Qu-Ab}}$ on Fig. 4) has a continuous decline, a minimum, or a maximum. In the ternary system Diops:Ab:An the eutectic line according to Bowen's experimental investigations (see Fig. 6) has a continuous decline from $E_{\text{Diops-An}}$ (at 1270°) to $E_{\text{Diops-Ab}}$ (at a little below

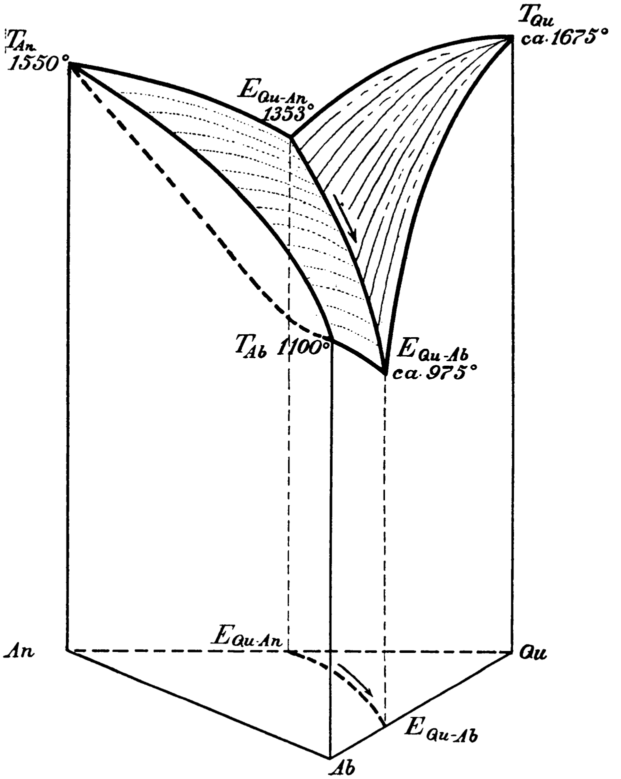

FIG. 4.—The ternary system An:Ab:Qu

---

[1] *Zeitschr. f. physikalische Chemie*, 1905, Vols. 50, 51, and 52.

[2] This term I have used in my earlier treatise. Boeke (*loc. cit.*) uses the shorter term "eutectic line."

1100°), consequently with a difference of *ca.* 200° between the two points.

For the analogous system Qu:Ab:An, where the difference between the two points (E_{Qu-An} at 1350° and E_{Qu-Ab} at probably a little below 1000°) is still greater, certainly at least 350°, we may also suppose a continuous decline for the eutectic line. This line, on account of the steep decline near Ab of the binary liquidus curve between An and Ab, will probably assume the course outlined on the horizontal projection, Figure 5. The crystallization between Ab+An and Qu has consequently the same course as between Ab+An and diopside (see below). Even if the curve between E_{Qu-An} and E_{Qu-Ab}, contrary to our conjecture, should show a maximum in the vicinity of E_{Qu-An} or a minimum in the vicinity of E_{Qu-Ab}, this would in no degree worth mentioning modify the course of the curve in the horizontal projection.

We calculate the chemical composition of the end members and of a pair of intermediate compositions.

TABLE III

Percentage of		E_{Qu-Ab}	$E_{Qu-Ab+An}$ by		E_{Qu-An}
			¾ Ab:¼ An	½ An:½ Ab	
	Qu	28	36	42	48
Ab+An	Ab	72	48	29	....
	An	....	16	29	52
	SiO_2	77·75	75·95	74·5	70·5
	Al_2O_3	13·95	15·2	16.25	19.0
	CaO	....	3·2	5·85	10.5
	Na_2O	8.50	5·65	3·4	....

That the calculation here given of the eutectic between quartz and albite, oligoclase, etc. (which is supported by the theoretical argument on the eutectic Qu:An at the pressure of one atmosphere, and by analogy conclusions according to the composition of microcline graphic granite) is essentially correct, is confirmed by the close conformity between the two analyses, Nos. 12 and 13, of oligoclase graphic granite and the compositions here calculated, especially for ¾ Ab:¼ An.

For the system *Quartz*:*Orthoclase* (microcline, with about 72 Or+28 Ab_{+An}):*Albite* (with about 88 Ab or Ab_{+An} and 12 Or) we must have three individualization-fields, with partial eutectics respectively about 26 Qu:74 orthoclase (72 Or+28 Ab), about 26 Qu:74 Albite (Ab with little An and about 12 Or) and about 40 Or:60 Ab_{+An} (or 42:58). If we leave the inconsiderable admixture of An out of consideration, we must suppose for Qu:Or: Ab a ternary eutectic, with about 26 Qu and about 42 Or:58 Ab, consequently about 26 Qu:31 Or:43 Ab (or Ab_{+An}).

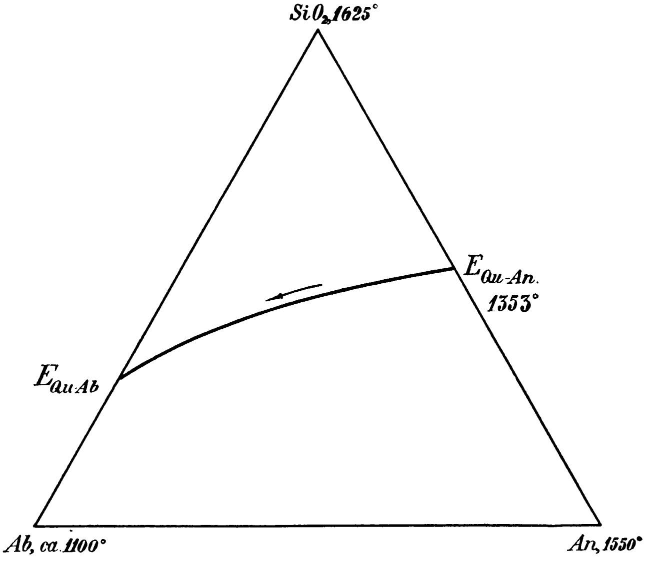

FIG. 5.—The ternary system Ab:An:SiO_2 (horizontal projection)

We calculate the composition of these eutectics (see *Tscherm. Mitt.*, Vol. XV [1906], p. 385) as shown in Table IV.

TABLE IV

APPROXIMATE CALCULATION OF EUTECTICS QUARTZ: ORTHOCLASE (MICROCLINE): ALBITE (WITH LITTLE AN)

Percentage of	Eutectic Qu:Orthoclase (72 Or:28 Ab+An)			"Ternary Eutectic" Qu:Orthoclase:Albite (with 42 Or:58 Ab+An)				Eutectic Qu:Albite (88 Ab or Ab+An:12 Or)			
Qu	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	28.0	32.0
Or	53.3	53.3	53.3	31.1	31.1	31.1	31.1	8.9	8.9	8.7	8.6
Ab	20.2	19.2	17.7	42.4	41.4	39.9	36.9	64.6	63.6	60.3	53.4
An	0.5	1.5	3	0.5	1.5	3.0	6.0	0.5	1.5	3.0	6.0
SiO_2	74.7	74.45	74.05	75.55	75.3	74.9	74.15	76.45	76.2	76.45	76.9
Al_2O_3	13.85	14.0	14.25	14.1	14.25	14.55	15.05	14.35	14.5	14.4	14.15
K_2O	9.0	9.0	9.0	5.25	5.25	5.25	5.25	1.5	1.5	1.45	1.45
Na_2O	2.35	2.25	2.1	5.0	4.9	4.7	4.35	7.6	7.5	7.1	6.3
CaO	0.1	0.3	0.6	1.0	0.3	0.6	1.2	0.1	0.3	0.g	1.2

TABLE V

Percentage of	Andesites				Dacite	Spherulit Rock	Dacite	Quartz-porphyry	
	Emmons		(Idd.)	(Lag.)	(Idd.)	(Lag.)	(Lag.)	(Lasp.)	(Streng)
	14*a*	15*a*	16*a*	17*a*	18*a*	19*a*	20*a*	21*a*	22*a*
SiO_2	59.06	60.39	62.00*	62.54	69.36	76.48	75.07	72.24	74.11
Al_2O_3	16.40	16.96	17.84	23.56	16.23	12.09	12.15	13.63	13.69
Fe_2O_3	2.88	1.50	......		0.88	0.95	1.67	......	......
FeO	4.18	3.42	4.40		1.53	......	......	3.05†	1.75
MgO	2.63	3.81	2.64	1.15	1.34	0.39	0.14	0.66	0.05
CaO	4.32	5.41	5.37	4.75	3.17	0.64	0.86	0.95	1.38
Na_2O	5.29	3.37	4.29	3.16	4.06	4.89	4.12	2.95	1.54
K_2O	1.49	2.01	1.47	2.43	3.02	3.78	4.57	5.24	5.67
H_2O, ign	2.06	2.03	1.66	1.75	0.45	0.77	1.34	1.26	0.56
Total	98.31	99.11	100.13	99.35	100.04	99.96	99.92	100.11	99.90

	Phenocrysts								
	(14*b*)	(15*b*)	16*b*	17*b*	18*b*	19*b*	20*b*		22*b*
SiO_2	56.25	55.92	56.41	55.42	(65.77†)	62.14	65.49	......	61.80
Al_2O_3	28.56	28.58	27.39	28.01	21.51	22.30	18.74	......	19.28
Fe_2O_3	0.77	1.00	0.69‡	1.09	tr.	tr.	tr.	......	2.02
MgO	1.06	0.55	0.09	tr.	0.00	tr.	......	......	0.01
CaO	6.54	6.65	9.87	9.12	5.72	3.29	0.39	......	......
Na_2O	5.42	5.66	5.43	5.10	5.92	10.58	3.53	......	0.68
K_2O	0.61	0.66	0.30	0.79	0.83	1.69	9.45	......	12.18
H_2O, ign	0.33	0.69	......	0.52	0.34	0.20	1.30	......	0.25
Total	99.54	99.71	100.24	100.05	100.09	100.20	98.90	......	100.10

	Glass Basis						Groundmass		
	14*c*	15*c*	16*c*	17*c*	18*c*	19*c*	20*c*	21*c*	22*c*
SiO_2	68.11	68.60	69.94	70.19	76.75	74.59	74.96	74.41	74.44
Al_2O_3	15.56	17.27	15.63	17.19	12.32	12.88	13.67	13.39	13.51
Fe_2O_3	0.96	2.09	....		.....	0.80	1.80	......	......
FeO	2.12	0.58	1.89		1.36	......	......	3.08	2.25
MgO	1.10	0.40	0.28	0.53	0.00	0.30	tr.	0.50	0.01
CaO	2.91	1.72	2.49	2.50	1.18	0.76	0.62	1.38	1.19
Na_2O	3.43	3.30	3.83	3.30	3.55	3.30	2.70	3.27	1.40
K_2O	2.61	4.61	2.85	3.89	3.98	5.35	4.14	4.18	5.31
H_2O, ign	2.82	2.08	3.25	2.31	0.54	1.03	1.52	1.04	1.34
Total	99.62	100.65	100.16	99.91	99.68	99.01	99.41	101.55	99.45

* +0.17 TiO_2, 0.29 P_2O_5 in the rock.

† In the rock 0.13 and in the groundmass 0.30 per cent MnO.

‡ is FeO.

EXPLANATION

Nos. 14 and 15: H. Emmons, "Island of Capraja, at Elba," *Quart. Jour. London*, 1893. The two feldspars 14*b* and 15*b* isolated by density 2.67—No. 16: A. Hague and J. P. Iddings, "Volcanoes of Northern California, Oregon, and Washington Territory," *Amer. Jour. Sc.*, 3, Vol. XXVI (1883). Hypersthene-andesite.—No. 17: A. Lagorio, "Über die Natur der Glasbasis sowie der Krystallisationsvorgänge in eruptiven Magma," *Tscherm. min. u. petrogr. Mitt*, Vol. VIII (1887); from Hliniker Valley, Hungary.—No. 18: Hague and Iddings (*loc. cit.*); California. The plagioclase is andesine-oligoclase. The determination of SiO_2 in the plagioclase is too high, owing to impurity.—No. 19: Lagorio (*loc cit.*). Spherulitic rock; from Alausi, Ecuador.—No. 20: Lagorio (*loc. cit.*); from Summit County, Colorado. With phenocrysts of quartz and two feldspars, one monocline (analysis No. 20*b*) and the other tricline.—No. 21: Laspeyres (see Zirkel's *Textbook of Petrography*, 1894, Vol. II, p. 177); from Halle, Germany.—No. 22: A. Streng, *Neuer Jahrb. f. Min., Geol. u. Pal.*, 1860, from the Harz Mountains.

In order to establish that the crystallization in the eruptive magmas of the different feldspars and of quartz is in conformity with the physicochemical details which we here have developed essentially on the basis of the analysis of graphic granite, we refer *inter alia* to my earlier statement in *Tscherm. Mitt.*, Vol. XXV (1906).

On pages 340 and 342 we give a small selection (analyses Nos. 14–29) from the numerous analyses, compiled from the literature, partly of porphyritic rocks, with special analyses of (*a*) the whole rock, (*b*) the porphyritic feldspar, and (*c*) the glass or groundmass, and partly of some granites with special analyses of (*b*) the basic concretions (or orbicules), and (*c*) the inclosing rock.

Granites with basic concretions (Nos. 24*b*–26*b*), or basic orbs (Nos. 27*b*–29*b*) are shown in Table VI on p. 342.

We call special attention to the following:

1. In the intermediate and the acid eruptive rocks, which contain the ordinary admixture of ferromagnesian silicates and iron, or titanic iron, ore (especially magnetite and ilmenite), an essential part of these minerals crystallizes at an early stage. A small quantity of Fe_2O_3, FeO, and MgO, however, is left in the remaining magma. This appears in the solidified rocks as the glass basis or groundmass in the porphyritic rocks, or as the intervening mass between basic concretions or orbicules in granites.

In the final, very complicated eutectic, chiefly consisting of feldspars and quartz, there usually seem to appear 0.5 per cent Fe_2O_3, 0.25 per cent FeO, and 0.1–0.25 per cent MgO; the figures,

TABLE VI

Percentage of	Basic Concretions					Basic Orbs			
	23b	*24b₁*	*25b₁*	*25b₂*	*26b*	*27b*	*28b*	*29b₁*	*29b₂*
SiO_2	53.80	54.73	56.01	56.53	64.39	55.72	65.57	61.10	68.02
TiO_2	0.77	tr.	1.13	1.40	tr.	0.57	......	0.51	......
Al_2O_3	19.20	14.02	15.19	16.47	15.99	21.35	17.46	15.55	15.31
Fe_2O_3	7.60	2.34	2.34	1.58	1.47	.....	4.15	2.10	0.59
FeO		4.92	4.89	5.40	5.98	8.81		2.21	2.14
MnO	......	......	0.40	0.20	tr.	0.36	......	......	......
MgO	4.80	7.40	4.67	2.67	1.67	0.63	2.53	6.30	3.41
CaO	5.70	10.20	4.85	4.90	2.57	5.10	2.49	1.12	1.53
Na_2O	2.16	2.98	5.66	5.59	4.96	5.71	2.14	1.23	2.85
K_2O	5.08	2.67	2.16	3.80	2.46	1.23	4.23	9.38	5.67
P_2O_5	1.20	tr.	0.53	0.27	tr.	......	......	......	......
Ign.	1.28	1.23	1.26	0.93	0.95	0.46	1.26	1.80	0.46
Total	101.59	100.99	99.21	99.98	100.44	99.94	99.83	100.58	99.98

	Intervening Mass								
	23c	*24c*	*25c₁*	*25c₂*	*26c*	*27c*	*28c*	*29c*	
SiO_2	74.40	70.44	71.90	73.69	73.70	70.05	68.27	71.71	......
TiO_2	......	......	0.35	0.28	tr.	0.19	......	......	......
Al_2O_3	13.91	15.63	14.12	12.46	14.44	14.78	15.59	15.05	......
Fe_2O_3	1.39	1.34	1.20	1.21	0.43	......	2.13	1.11	......
FeO		1.12	0.86	1.75	1.49	3.37		0.29	......
MnO	......	......	0.05	0.15	tr.	0.22	......	......	......
MgO	0.28	0.55	0.33	0.17	tr.	0.44	1.19	0.56	......
CaO	0.61	1.98	1.13	0.36	1.08	3.42	1.93	1.42	......
Na_2O	4.65	4.03	4.52	4.47	4.21	3.10	3.21	3.39	......
K_2O	4.36	5.18	4.81	4.92	4.43	4.13	5.37	5.43	......
P_2O_5	......	......	0.11	0.04	tr.	......	......	......	......
Ign.	0.65	0.55	0.60	0.38	0.61	0.42	1.56	0.61	......
Total	100.25	100.82	100.35	100.09	100.39	100.12	99.25	99.77	......

EXPLANATION

No. 23: See Rosenbusch, *Elemente der Gesteinslehre*, 1901; from Pelvoux.—No. 24: Graber, *Jahrb. d. k.-k. geol. Reichsanstalt*, Wien, 1897; from Topla in Carinthia.—No. 25: Clarke, *U.S. Geol. Survey Bull. 168*, 24; from Mount Ascutney, Vt.—No. $25b_2$ and c_2, granite porphyry.—No. 26: J. A. Phillips, *Quart. Jour. London*, 1880; from Peterhead, Scotland.—No. 27: H. Bäckström, *Geol. Fören. Förh.*, Stockholm, 1894; from Kortfors, Sweden.—Nos. 28–29: K. v. Chrustschoff, "Über holokrystalline makrovariolithische Gesteine," *Mém. de l'académie des sc. de St. Pétersbourg*, 1894. No. 28 from Altai; No. 29 from Fonni, Sardinia.

however, especially for MgO, depend somewhat upon the Mg-bearing mineral component in question (biotite, hypersthene, etc.).

2. As previously mentioned and as illustrated by analyses Nos. 14–19 and 20–22, plagioclase crystallizes when there is a surplus of Ab+An; orthoclase, on the contrary, when there is a surplus of Or in the original solution. The boundary lies, as previously explained, at about 0.4 Or:0.6 Ab+An. In the plagioclase which crystallized first, relatively much An appears, consequently relatively much CaO (and Al_2O_3) (cf. the analyses Nos. 14*b*–19*b*). In consequence, the remaining magma shows a decreasing percentage of CaO, and this in the "granite eutectic" falls to 0.25, 0.5, or 1 per cent CaO, or, with predominating plagioclase in the eutectic, not quite so low.

If we leave magmas with only a trifle of Na_2O (Ab), or of K_2O (Or), out of consideration—where the crystallizing orthoclase absorbs practically all of the Ab or the crystallizing albite or albite-oligoclase the Or—the contents of Or (or K_2O) in the magma remnant increases by the crystallization of plagioclase (cf. the analyses Nos. 14*c*–19*c* and 24*c*, 27*c*), and the contents of Ab (or Na_2O) in the magma remnant increases by the crystallization of orthoclase (cf. No. 21*c*). But we especially emphasize that this *relative increase has a limited course*, and that *the limit of about 0.4 Or:0.6 Ab or Ab+An is not exceeded*, or only perhaps now and then somewhat exceeded because of supersaturation. In this matter we especially refer to the analyses of the glass basis or groundmass of porphyritic rocks. In judging these analyses, however, we must take into consideration that the glass, as is shown, for example, by the water content, is always or nearly always somewhat decomposed, whereby especially a little alkali will be extracted. We further refer to the intervening material between basic concretions or orbicules in granites.

As examples these intervening masses from casually chosen granites show:

In Nos. 28 and 29, where orthoclase crystallized first, respectively 0.45 Or:0.55 Ab_{+An} and 0.46 Or:0.54 Ab_{+An}.

In No. 23, where both orthoclase and plagioclase seem to have crystallized at an early stage: 0.37 Or:0.63 Ab_{+An}.

In Nos. 24, 25c^1 and c^2, 26, and 27, where plagioclase (or perhaps predominant plagioclase and some orthoclase) crystallized at an early stage, respectively: 0.40, 0.38, 0.41, 0.38, and 0.36 Or. The remainder is Ab_{+An}.

These values, calculated from the analyses, for the proportions Or:Ab_{+An} need, however, a small correction, as we have taken for granted that the whole quantity K_2O, Na_2O, and CaO form respectively Or, Ab, and An, while in reality a trifle K_2O (and a still smaller amount of Na_2O) in several cases enters into biotite.

3. The glass basis, or the groundmass, in andesites (with at least about 56 per cent SiO_2, that is to say, with at least so much SiO_2 that a little of the independent component quartz entered into the melted magma) and also in dacites, trachytes, rhyolites, quartz-porphyries, etc. (with max. about 72 per cent SiO_2) without exception shows an increased percentage of SiO_2 as compared with the entire rock. Gradually as the crystallization, for example, of an andesite with 59 per cent SiO_2 (No. 14*a*) advances with solidification of magnetite, ferromagnesian silicates, and medium-basic plagioclase, the temperature drops, and simultaneously the mother liquor becomes richer in SiO_2. By rapid cooling the viscosity increases and causes the cessation of the crystallization; in other words, the fluid remnant stiffens into glass, with varying percentages of SiO_2 according to the time at which the crystallization ceased. And this point of time may lie even considerably lower than the stage of the final eutectic. This we may illustrate by giving the percentages of SiO_2 in the entire rock and in the glass basis (or in some cases the groundmasses); the latter, however, always contains a little H_2O, showing that it is somewhat decomposed. (See my treatise in *Tscherm. Mitt.*, Vol. XXIV [1905].)

ANDESITES

Percentage of SiO_2 in									
Rock	56.8	57.8	58.1	59.1	60.1	60.4	62.0	62.3	62.5
Glass basis	64.5	65.1	70.8	68.1	68.7	68.6	69.9	67.0	70.2

DACITES

Percentage of SiO_2 in						
Rock	65.6	68.3	69.4	65.5	65.3	67.3
Glass basis	71.9	74.8*	76.75	70.2	70.2 and 73.6	72.4

* Goundmass.

Further we include a series of rhyolites, dacites, spherulites, and quartz-porphyries, in which phenocrysts of feldspar (orthoclase or plagioclase) as well as of quartz usually appear. Gl. = glass basis; Grm. = groundmass; Sph. = Spherulite.

TABLE VII

	PERCENTAGE OF	DACITES		RHYOLITES					SPHERULITIC ROCKS		
		Sph.	Grm.	Grm.	Sph. and Gl.	Gl.	Sph. Gl.		Gl.	Sph. Gl.	
Rock	SiO_2	74.6	75.07	72.5	75.8	73.0	71.4		76.5	72.8	
Gl., Grm.,	SiO_2	76.05*	74.96	77.5†	72.7	72.6	74.5	72.5	74.6	73.7	70.7
or Sph...	H_2O	1.2	1.5	1.4	0.9	4.55	1.4	4.4	1.0	1.4	3.7

*Only 10.24 per cent Al_2O_3. Somewhat decomposed.

†Only 11.52 per cent Al_2O_3. Somewhat decomposed.

	Percentage of	Spherulitic Rocks with Spherulites and Glass Basis					Quartz-Porphyries with Groundmass			
Sph.	SiO_2	73.2	74.4	75.4	73.4	Qu-porph...	72.0	72.2	74.1	75.2
Gl.	SiO_2	72.4	72.7	73.0	73.1	Grm.	74.0	74.4	74.4	(76.8?)
	H_2O	1.4	1.1	3.6	0.9			1.0	1.3	0.8

The glass basis, or the groundmass, in the porphyritic rocks consequently shows:

a) In rocks with about 60 per cent SiO_2, a sometimes very considerable increase in the percentage of SiO_2 (for example, from 58.1 to 70.8 per cent SiO_2) and in rocks with about 65 or 65–70 per cent SiO_2 a smaller increase, though in undecomposed state not above 75 per cent SiO_2.

b) In rocks with about 73–75 per cent SiO_2 we find, on the other hand, about the same percentage of SiO_2 in the glass basis or groundmass as in the entire rock. The analyses show some slight variations, partly in one and partly in the other direction. But this is certainly caused in some cases only by slight inaccuracies in the relatively old analyses, and in others by the groundmass and especially the glass basis (probably without exception) being a little decomposed, as shown by a little H_2O.

These law-governed relations, which are established by numerous analyses, may depend on the fact that in a magma consisting chiefly of Qu and Or, Ab and An components, with a surplus of feldspar components, the crystallization of feldspar may continue without a simultaneous secretion of quartz until the eutectic boundary-line between quartz and the feldspar components has been reached. When this has occurred, however, a simultaneous crystallization of feldspar and quartz commences, with only a quite inconsiderable change of the SiO_2 percentage of the magma remnant, while we constantly more and more approach the "ternary" eutectic: Qu:Or:Ab+An (with a trifle magnetite and ferromagnesian silicate).

The groundmass in the quartz porphyries and the closely related rocks consists, as is well known, in some cases of microfelsite and in others of granophyre, and these structural forms indicate a *simultaneous* crystallization of quartz and the feldspar in question. The final crystallization consequently took place also with regard to the structure at a eutectic or eutectic boundary-line.

Especially acid quartz porphyries (with more than 75 per cent SiO_2) show phenocrysts of quartz and feldspar in about equal amounts, but groundmasses of normal microfelsite or granophyre, that is to say, with relatively less quartz than among the phenocrysts. The groundmass, consequently, here must have grown a little more basic than the original rock. I lack material, however, to prove this by chemical analysis.

If we now turn to the deep-seated igneous rocks, we find that the quartz-norites and quartz-gabbros (with about 1 to 5 or 6 per cent quartz), the quartz-diorites, the quartz-syenites, etc., prevailingly show that the quartz first began crystallizing at a relatively late stage. As we shall explain later (Figs. 17 and 18) when treating of the quartz-norites, this crystallization of quartz at a late stage took place, not by itself, but simultaneously with the final crystallization of the feldspar (the plagioclase) and the ferromagnesian silicate in question. In the granite porphyries, which contain but little ferromagnesian silicate and magnetite but are especially rich in feldspar, with about 66–70 per cent SiO_2, the crystallization commenced with the solidification of some feldspar.

The crystallization in ordinary granites usually commenced with a solidification of some magnetite and ferromagnesian silicate, while the feldspar first commenced crystallizing at a somewhat later stage. The sequence of the *commencement* of the crystallization in the granites is in most cases (1) pyrite, zirkon, apatite, etc.; (2) iron ore and ferromagnesian silicate; (3) feldspar; (4) quartz. But it appears from the structure that the ferromagnesian silicate, especially biotite, continued crystallizing after the commencement of the solidification of both feldspar and quartz, and that the feldspar continued crystallizing also during the segregation of the quartz. In most of the granites, however, we are unable to determine with accuracy from the structure, the quantitative proportions of feldspar and quartz during the intermediate and later stages of the crystallization.

The case is complicated by the fact that the granite magma contains, besides the usual ferromagnesian silicate, Or, Ab, An, and Qu components, some H_2O, probably partly entering into a SiO_2 combination, for example, as H_2SiO_3 (?), and the latter was not split up until a later stage of the crystallization period. If this supposition is correct, the consequence will be a somewhat reduced quantity of the independent quartz component during the first part of the crystallization period—that is to say, during the first part of the crystallization the feldspar was relatively more abundant than that corresponding to the proportion calculated from the relation between feldspar and quartz in the resulting solid rock.

We have an instructive orientation on the composition of granite magmas at a late stage of the solidification in the composition of the intervening masses between basic concretions, or orbicules, in granites, which show these structural elements. (See analyses Nos. 23*c*–29*c*.) These intervening masses prove throughout that during the crystallization a displacement of the composition of the magma remainder took place in the direction of the—in other ways determined—"granite eutectic," and we especially emphasize that the analyses of the intervening masses Nos. 23*c*, 25c_2, and 26*c* almost exactly correspond with the "granitic eutectic."

Above we have only considered granites with relatively basic concretions, or orbicules. But from strongly *acid* granites, with about 78–80 per cent SiO_2 in the whole rock, we know a couple of examples[1] of orbicular structure, the orbs chiefly consisting of *quartz*, and in addition some sillimanite and tourmaline (!). The intervening mass between the orbs here contains less SiO_2 (and less quartz) than the orbs, therefore reckoned from the acid pole there here appears a displacement of the residual magma in the direction of the eutectic, quartz:feldspar. In these cases we have, however, the complication that the orbs contain much tourmaline and sillimanite, the latter being very little soluble in acid magma.

Finally we compile a series of analyses of glass bases (Gl.), respectively groundmasses (Grm.), and spherulites (Sph.) from porphyritic rocks, and intervening masses from granites with basic concretions, etc. These analyses represent approximately the composition of the residual magmas resulting from far-advanced

TABLE VIII

ANALYSES OF THE FINAL PRODUCT OF THE CRYSTALLIZATION OF ACID ROCKS—THE GRANITIC EUTECTIC

	No.	SiO_2 Without H_2O	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Total
Gl., Sph......	30	73.4	72.69	.....	15.04	....	tr.	0.25	1.75	8.85	0.94	**99.52**
Grm..........	31	74.0	74.0	.....	.....	....	....	....	0.60	7.57	....	......
Glass basis....	32	73.4	72.44	.....	16.28	....	0.20	0.59	2.12	6.49	1.35	**99.47**
	33	74.4	73.57	13.80	.....	1.54	0.26	0.99	3.09	5.74	1.08	**100.07**
	34	73.3	72.35	13.97	1.29	....	0.46	0.72	3.58	5.38	1.37	**99.12**
	35	73.7	73.05	14.67	0.89	....	0.26	0.97	3.99	5.11	0.91	**99.85**
	19*c*	75.3	74.59	12.88	0.80	....	0.30	0.76	3.30	5.35	1.03	**99.01**
Intervening mass of granites....	25c_2	74.0	73.69	12.46	1.21	1.75	0.17	0.36	4.47	4.92	0.38	**100.09**
	23*c*	74.9	74.40	13.91	1.39	....	0.28	0.61	4.65	4.36	0.65	**100.25**
	26*c*	74.1	73.70	14.40	0.43	1.49	tr.	1.08	4.21	4.43	0.61	**100.39**
Spherulites...	36	74.0	73.21	12.90	2.10	....	0.27	0.88	4.83	4.75	1.04	**99.98**
	37c_1	75.1	74.52	12.97	2.02	....	0.25	0.92	4.26	4.53	0.83	**100.30**
	38	74.7	73.72	12.91	1.37	....	0.25	1.37	4.02	4.45	1.36	**99.45**
Gl...........	39	73.5	72.70	13.79	1.01	....	0.65	2.07	4.93	4.33	1.10	**100.48**
Sph..........	37c_2	74.0	73.42	14.29	1.01	....	0.43	1.00	5.61	3.19	0.84	**99.79**
	40	74.8	74.36	14.46	1.62	....	0.44	1.49	6.11	1.49	0.57	**100.54**

---

[1] From Kragerö and Modum in Norway and from Pine Lake in Ontario (lecture by W. C. Brögger on the Kragerö locality, in *Kristiania Vidensk. Seisk*, 1901, and Frank D. Adams, *Bull. Geol. Soc. Amer. No. 9*, 1898, see résumé in my treatise in *Tscherm. Mitt.*, Vol. XXV [1906]).

EXPLANATION

No. 30: Spherulitic glass basis from liparites.—No. 31: groundmass from quartz-porphyry.—Nos. 32, 33: Glass basis from trachytes.—Nos. 34, 35, 39: Glass basis from spherulitic rocks—Nos. 36, 37c_1 and c_2, 38, and 40: Spherulites from spherulitic rocks.

Nos. 30, 32, 34, 35, 36–40 reprinted from the above-cited excellent treatise of Lagorio, 1887.—No. 31, see Zirkel's textbook.—No. 33, Williams, *Neues Jahrb. f. Min., Geol. u. Pal.*, Beil., Bd. V, 1887 (see also my treatise in *Tscherm. Mitt.*, Vol. XXIV [1905]).

crystallization. In judging these analyses we must take into consideration that throughout a little alkali was probably extracted from the glass basis, so that the determined percentages of alkalies may be a trifle too low. The analyses are generally arranged according to decreasing K_2O (Or) or increasing Na_2O (or Ab+An).

We especially direct attention to the close accordance between these analyses of the residual magmas resulting from the solidification—partly from dike and surface rocks, and partly from deep-seated rocks[1]—and the eutectic Qu:Or:Ab+An, calculated on the basis of the graphic-granite analyses and the theoretical explanations. (See the table, p. 339.) The accordance is especially pronounced when we take into consideration that the percentage of SiO_2 in the analysis of graphic granite will be reduced about 1 per cent when 1 or 2 per cent of ferromagnesian silicate and magnetite is added, and that the analyses of groundmasses, etc., which are rich in plagioclase, contain a little more CaO (or An) than the graphic granites calculated in the table, page 339, where only a small admixture of An is presupposed. The analyses in the table, page 348, of the residual magma represent the *granitic eutectic*, consisting of predominant Qu, Or, and Ab+An, with the addition of quite small admixtures of iron oxide (Fe_3O_4) and ferromagnesian silicate.

If we leave the latter quite subordinate admixtures out of consideration, the analyses Nos. 25c_2, 23c, 26c, 36, 37c, and 38 almost exactly represent the "ternary" eutectic Qu:Or:Ab (or Ab+An) with nearly exactly 0.4 Or:0.6 Ab (or Ab+An). And this we may by a short catchword name the *"ternary" granitic*

---

[1] Regarding the inconsiderable influence of the pressure on the composition of the eutectic we refer to a following chapter.

eutectic. This term strikes the essential point, since the eutectic in question consists practically only of Qu, Or, and Ab. To this must, however, be added a quite small admixture of An, iron oxide, and ferromagnesian silicate, so that the eutectic in reality is more complicated. In order to avoid misunderstanding I have therefore put the term "ternary" in quotation marks.

[*To be continued*]